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# Electrical Design of Space Shuttle Payload G-534 The Pool Boiling Experiment

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# **ELECTRICAL DESIGN OF SPACE SHUTTLE PAYLOAD G-534 THE POOL BOILING EXPERIMENT**

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## **ABSTRACT**

Payload G-534, the Pool Boiling Experiment (PBE), is a Get Away Special (GAS) payload that flew on the Space Shuttle Spacelab Mission J (STS 47) on September 19 - 21, 1992. This paper will give a brief overall description of the experiment with the main discussion being the electrical design with a detailed description of the power system and interface to the GAS electronics. The batteries used and their interface to the experiment Power Control Unit (PCU) and GAS electronics will be examined. The design philosophy for the PCU will be discussed in detail. The criteria for selection of fuses, relays, power semiconductors and other electrical components along with grounding and shielding policy for the entire experiment will be presented. The intent of this paper is to discuss the use of military tested parts and basic design guidelines to build a quality experiment for minimal additional cost.

## **EXPERIMENT OVERVIEW**

The Pool Boiling Experiment (PBE) purpose is to experimentally determine the effect of heat flux and liquid subcooling on nucleate pool boiling in a long term reduced gravity environment. Nucleate boiling is a mode of heat transfer where relatively small temperature differences can provide large rates of heat transfer. This results in significantly smaller heat transfer areas to accomplish the same transfer of heat.

The experiment is performed by heating the test fluid (R-113) to 120 F with a uniformity of  $\pm 0.4$  F. After this temperature and uniformity are achieved, the pressure on the fluid is lowered to a designated subcooling (20, 5 and 0 degrees subcooled) then power is applied to a thin (400 Å) gold film heater that has a surface area of  $7.25 \text{ cm}^2$ . Three different power levels are applied throughout the testing: 2, 4, and  $8 \text{ W/cm}^2$ . By changing the subcooling and power levels, a total of 9 different tests are performed during flight. While power is applied to the heater, temperature and pressure data are recorded. During the tests the camera is operated at 10 frames per second (FPS) and 100 FPS to capture nucleation on film. Each of the components required to perform the test is discussed in the following sections.

The PBE structure consist of two shelves that are connected together with brackets (see Figure 1.0). The experiment chamber is located between the two shelves and contains all of the science instrumentation, the thin film gold heater and the test fluid (R-113). The batteries (2) and the Data Acquisition and Control System (DACS) are located on the top shelf. The batteries provide

power to all of the components and the DACS controls all of the experiments components and acquires the data. Other components are the triaxial accelerometer, boiling heater power supply, camera, stirrer, lights, and Power Control Unit (PCU).

## **ELECTRICAL SYSTEM DESCRIPTION**

The electrical system for PBE was designed using two silver zinc batteries as the power supply. The batteries power seven major components and the PCU. The components were divided into two separate groups (busses) so that the electrical "noisy" components would not interfere with the data and control system. The following is a brief description of each component and its power requirement.

### **Data Acquisition and Control System (DACS)**

The DACS consists of a STD bus system with a CPU card and five additional cards (See Figure 2.0). The CPU, memory and A/D card are bought from a commercial vendor with upgrades. These upgrades consisted of changing the parts from plastic to military screened ceramic components, see the section on Electrical Parts Selection for additional details. The CPU card is a 16 bit single board computer, 80C88, operating at 5 MHz. The memory card is populated with eight 32K x 8 EEPROMs which gives PBE the capability of storing 256 KBytes of data. The A/D card is a 15 channel, 12 bit A/D configured in a unipolar 0 to 10 V mode. The other three cards were designed in-house and fabricated to Military Specification Mil-P-55110D. For more details on the fabrication and layout design, see the section on Printed Circuit Boards. The three in-house designed cards are the pressure control, thermistor multiplexer and the I/O-camera synchronizing.

The Pressure Control card contains a hardware logic controller which maintains the pressure in the test chamber to  $\pm 0.1$  PSI by reading the output of the chamber pressure transducer and comparing this reading to the required setpoint (from DACS). After this comparison (this is a real time continuous process), the appropriate solenoid valve is commanded opened as required. The fill solenoid valve is connected to a nitrogen gas supply and the vent solenoid valve is open to the GAS can volume.

The Thermistor Multiplexer card provides two main functions: signal conditioning for the science thermistors (temperatures), and multiplexing 15 signals into 1 A/D channel. The signal conditioning is performed using a four resistor bridge with a highly stable voltage reference. The four resistor bridge circuit provides the greatest resolution possible over a given temperature range.

The I/O-camera synchronizing card performs two main functions. The first function is general I/O capability for the DACS. The second function is to synchronize the LEDs that are in the field of view of the camera (these LEDs display a binary time count so that each frame of film is time tagged) with the shutter of the camera. This feature prevents the LEDs from being blurred on the film.

The total power consumed by the DACS system which includes the DC/DC converter is approximately 6.25 Watts.



## **Thermal Strip Heaters**

The experiment test chamber has strip thermofoil heaters mounted to all external surfaces. The heaters provide  $5 \text{ W/in}^2$  of power to the chamber so that the test fluid may be heated to 120 F. The heaters have aluminum backing with Kapton insulation, 24 gauge leads and are mounted using pressure sensitive adhesive (PSA). The heaters are divided into two electrical circuits with group #1 consisting of 70 Watts and group #2 consists of 80 Watts. Each group is also over temperature protected with two thermostats.

## **Stirrer**

A stirrer is used to mix the test fluid prior to each test sequence. This mixing provides for an even distribution of heat from the thermal strip heaters. The stirrer is a DC permanent magnet planetary gearmotor that consumes 3 Watts.

## **Solenoid Valves**

Two solenoid valves are used to regulate the pressure in the test chamber (See DACS section). Each valve is a direct-acting, fast response, 2-way normally closed valve having bubble tight construction. Each valve requires approximately 9 Watts when operated.

## **Boiling Heater Power Supply**

The Boiling Heater Power Supply (BHPS) is a multiple setpoint regulated voltage power supply that provides the three different power levels required for the thin film gold heater. The BHPS requires between 10 and 75 Watts of power depending on the setpoint.

## **Camera**

A 28 Volt, 16 mm movie camera is used to film the nucleation process. The camera operates at two frame rates, 10 and 100 frames per second (FPS). Two frame speeds were required since only 18,000 frames of film were available and it is desired to capture the onset of nucleation at the faster frame rate and film the steady state boiling. The camera requires 25 Watts at 10 FPS and 45 Watts at 100 FPS.

## **Lights**

Two lights are required to illuminate the test chamber for filming. The bulb type chosen is a 24 Volt,

20 Watt halogen bulb. Each light is driven at 11 Watts for 10 FPS filming and 20 watts for 100 FPS filming.

### **Accelerometer**

A triaxial accelerometer unit is included with the PBE. This device measure accelerations in the range of 0 to 50 milli-g with a resolution of 30 micro -g. The power required is approximately 1 Watt.

### **Power Control Unit (PCU)**

The power control unit contains a triple output DC/DC converter and EMI filter. The PCU routes and controls power to all of the experiments components and signal conditions engineering instrumentation. See the section on the Power Control Unit for more details. The PCU requires approximately 5 Watts of average power during operation.

### **Science and Engineering Instrumentation**

The science instrumentation includes the thermistors internal to the test chamber, the pressure reading of the test chamber and the voltage and current applied to the thin film gold heater. The *engineering or housekeeping parameters included battery voltages, currents and temperatures.* A feedback of the status of I/O lines was also stored in the data.

### **Power Profile and Batteries**

The total energy required to operate the PBE is 420 Watt-hours. Each 28 Volt (nominal) battery is comprised of nineteen 15 amp-hour, silver-zinc cells (See Figure 3.0). The total battery capacity was calculated by assuming worst case conditions. These conditions are after 3 months storage and operating at 32 F. These conditions were assumed due to the integration time for a GAS can, the shuttle attitude and the early operation of PBE during flight. The total capacity of the battery under these conditions was calculated as 765 Watt-hours. When designing an experiment with batteries it is prudent to have a 1.5 to 2 margin of energy available at worst case conditions versus energy required. This capacity must also be verified by testing.

This concludes the description of the overall electrical system. The following section describes the interconnecting of the entire electrical system.

## **HARNESSING, CONNECTORS, WIRE AND FUSING**

### **Connectors**

All of the non-hermetic connectors for PBE meet Military specification MIL-C-26482. The shell of these connectors are aluminum alloy with a finish of electroless nickel per MIL-C-26074. The insulators are a rigid dielectric and the contacts are copper alloy with gold plating per MIL-G-45204. The rated operating temperature of these connectors is -55 C to 200 C. The hermetic connectors used in the test chamber and the battery boxes meet military specification MIL-C-38999. Environmental sealing is accomplished by an interfacial seal with individual raised tapered sealing barriers around each pin contact and a peripheral seal. The shell is constructed of fused tin steel with a stainless passivated finish. The insulator is compression glass. The contacts are made of nickel alloy with gold plating. The connectors are designed to operate over a temperature range of -65 C to 200 C. These connectors were chosen due to the tolerance to the environment, durability of the contacts, sure locking of the mating halves and the very low leak rate.

### **Wire**

All of the wire use in PBE is silver plated copper conductor with Teflon insulation. This wire meets military Specification 22759/11. The wire is rated for 600 V and 200 C. See the Wire and Fuse Derating Section for criteria on selecting wire size.

### **Fuses**

The fuses used the experiment meet military specification MIL-F-23419. The fuses are subminiature high performance fast acting instrument type fuses which are classified as style FM08 by the military specification.

### **Wire and Fuse Derating**

The policy used for wire type, size and fuse type and sizing follows the interpretation (Refer to Johnson Space Center memorandum ER-87-326) of NHB 1700.7A (NSTS 1700.7B). This memorandum covers the derating of wire and fuses for a space environment. The philosophy of this memorandum is that the circuit protectors (fuses) must be sized to protect against an educated short rather than a dead short. A educated short is defined as a current limited failure that allows current to flow in the protected wire at the ultimate trip limit of the fuse for an indefinite amount of time. Therefore the wire must be sized to withstand a load one and one half times the rating of the fuse. The design load for the fuse is equal to half of the fuse rating. The following examples use this criteria:



-20 gage, 200 C wire is not used to carry more than 3.5 amps of current and must be fused with a 7 Amp FM08 style fuse (This wire is rated for at least 10.5 Amps - 1.5 times fuse rating).

-16 gage, 200 C is not used to carry more than 4.5 amps of current and must be fused with a 10 Amp FM08 style fuse (This wire is rated for at least 15 Amps - 1.5 times fuse rating).

For comparison; If silver plated nickel conductor wire with Tefzel insulation (MIL-W-22759/18) which is rated at 150 C is used:

-20 gage, 150 C wire is not used to carry more than 2.5 amps of current and must be fused with a 5 Amp FM08 style fuse (This wire is rated for at least 7.5 Amps - 1.5 times fuse rating).

-16 gage, 150 C is not used to carry more than 3.5 amps of current and must be fused with a 7 Amp FM08 style fuse (This wire is rated for at least 10.5 Amps - 1.5 times fuse rating)

If multiple power lines are bundled together then the current capacity of each wire must be derated as follows: derate 86% if there are 2 load wires; derate 68% if there are 4 and 60% if there are 6 loaded wires in a bundle.

## POWER CONTROL UNIT

The Power Control Unit (PCU) routes power and control lines to and from the components. The PCU consist of two main sub-assemblies; a circuit card and a base with a lower compartment (See Figures 4.0, 5.0 and 6.0). Contained within the lower compartment is a triple output (+5, +/-15V) 15 Watt DC/DC converter and an EMI filter. The EMI filter is designed to reduce the input line reflected ripple current of the DC/DC converter. The filter module also offers input voltage transient protection and reverse voltage protection. The filter reduces the conducted electrical noise, and the converter is sealed in the lower compartment to reduce the radiated electrical noise. All penetrations to the lower compartment housing the filter and converter was made via EMI/RFI feed through capacitors. The feed through capacitors for the input power lines and outputs are 0.3 uF, 50V.

Mounted to the top of the lower compartment are non-latching relays. The relays are rated for 12 amps resistive load and they were derated dependent on the type of load (2 Amps for lights and 4 Amps for a motor). Non-latching relays were chosen because at power up all of the components would be at a known state (power off). Another factor for choosing non-latching relays is that only one control line is required. Since the the relays were not operated for extended duration (usually on the order of minutes), the power dissipated energizing the relay coils was not a concern. But one component, the stirrer, was operated for a longer duration (hours), so a solid state relay (SSR) was utilized. The SSR was mounted the the circuit board above the base. The SSR uses less overall energy than the non-latching electro-mechanical relay while operating. This is due to the absence of power required to energize a coil. A MOSFET driver was used to energize the relay coils. An optoisolator was also

used to keep the control lines isolated from the 28 Volts required to energize the coils (which was also the same bus used for power).

The PCU also provides signal conditioning for the battery voltages and currents. The battery voltages are signal conditioned by using a simple resistor divider that divides the battery voltage by a factor of four. The current signals are conditioned by using a  $0.02\ \Omega$ , 5 Watt shunt in the return line of each battery. This signal is amplified by a factor of 50 by an operational amplifier.

The fuses for the entire experiment are contained in the PCU. The subminiature fuse (style FM08) are mounted on the printed circuit board, this allowed for the minimum usage of space.

One single point ground for the batteries and the DC/DC converter output was maintained in the PCU. This allowed for a single reference for the entire experiment and the absence of ground loops (see the following section).

## **ELECTRICAL NOISE REDUCTION TECHNIQUES**

The following guidelines were used for the PBE in reducing electrical noise.

### **Harnesses**

- 1) Power leads twisted together.
- 2) 'Noisy' power leads twisted and shielded.
- 3) Low level signals twisted and shielded and made as short as possible.
- 4) Ground leads are placed in between signal leads and 'noisy' leads when in same connector.

### **Criteria For Grounding of Shields**

- 1) Both ends of a shield for a noisy load are grounded to chassis.
- 2) One end of a shield for a low level signals is grounded. This ground is brought through a connector using a separate pin. This pin is directly connected to the DC/DC converter return--AT THE DACS (the point where the A/D conversion is taking place). The shield is isolated (insulated) from the connector housings and the experiment.

### **Other Techniques for Noise Reduction**

- 1) Noisy DC/DC converters are placed in a shielded enclosure with EMI/RFI feed through capacitors. (Ferrite beads may be placed on the leads.)
- 2) Relay coils have diode suppression.
- 3) Noisy loads are on a separate power bus.
- 4) Single point ground maintained for each power bus and signal bus.
- 5) A diode is placed across inductive loads (stirrer and solenoid valves). A 0.1 micro-farad



capacitor is placed across the stirrer motor. Ferrite beads are placed on the stirrer leads.

Placing noisy electrical load on a separate bus from the DACS minimizes the conduction of noise. This eliminates the need to design electrical filters for each noisy component (or for the DACS).

### **Circuit Cards**

1) Multi-layered cards with a ground plane were used to minimize electrical noise on sensitive circuitry.

## **ELECTRICAL PARTS SELECTION**

The electrical parts for PBE were selected with the goal of increasing reliability. The highlights of the selection policy are listed below.

### **Integrated Circuits (ICs)**

Ceramic packages that are hermetically sealed and tested to MIL-STD-883 were selected for use on PBE.

### **Resistors and Capacitors**

Only established reliability resistors and capacitors were used. The components used have a failure rate of 0.01%/1000 hours or better. Components with a failure rate of 0.1%/1000 hours or better were acceptable but were used only when the component with a better failure rate was not available. Use of electrolytic capacitors was avoided.

### **Printed Circuit Boards**

The in house circuit boards are a laminate made with epoxy resin and continuous filament woven glass fabricate that is flame retardant. The material is classified under MIL-P-13949F as GFN. The circuit cards were designed to MIL-STD-275E, this specification list guidelines for all aspects of circuit board layout. The boards were fabricated to MIL-P-55110D.

## **GAS CAN INTERFACE**

PBE uses the GSFC barometric switch to activate the GAS can Relay A which switches battery power to the experiment. Relay B is used to signal the experiment that the astronauts/shuttle is entering a quiet acceleration period. Essentially Relay B is used to switch a signal to the DACS to initiate PBE. If relay B is not activated, PBE will automatically start 14 hours after launch.

## **FLIGHT RESULTS**

The experiment was completely successful and operated as designed with no failures encountered during the flight. Even during the test program which included thermal cycling and burn in at the box level and at the system level were any failures due to military tested electrical parts encountered.

All of the data was recovered and the science data has less than two counts of "electrical noise" (on a 12 bit system). The film data was also recovered with all of the desired views intact. The electrical system operated as designed and the batteries still had plenty of margin (more than 50%).

## **CONCLUSION**

By using military tested parts with good design practices which includes a thorough test program, the chances of having a failure during testing of an experiment or during flight is minimized. Even though the cost of the tested parts is higher (approximately three times), it's still a very small percentage of the total cost of the experiment. For the PBE the total additional cost for two flight units with spares was approximately less than 1% of total cost of the experiment. One failure of a component during testing will cost a substantial amount of money in manpower to correct. If a failure occurs during flight, the entire investment could be lost. Therefore it is prudent to invest in quality parts and in good design practices.

By following a few good design practices, the chances of having a successful experiment are greatly enhanced. The quality of the data recovered is also more meaningful.



## REFERENCES

1. Protection of Power Distribution Circuitry, Memorandum ER-87-326, Lyndon B. Johnson Space Center, January 1988.
2. Safety Policy and Requirements, NSTS 1700.7B, NASA, Lyndon B. Johnson Space Center, January 1989. (Formerly NHB 1700.7A).

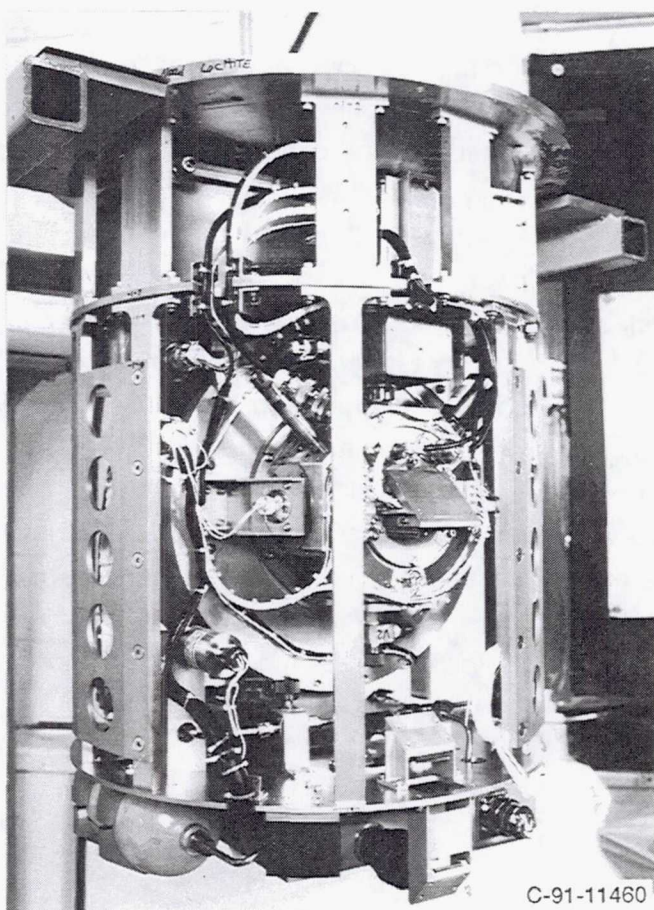


Figure 1.—Pool Boiling Experiment.



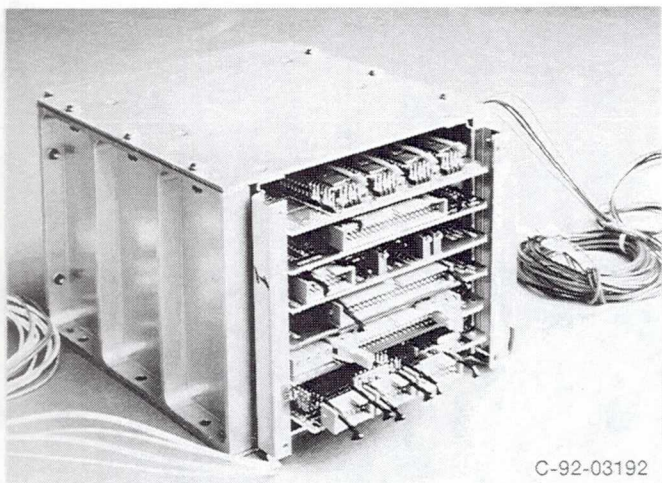


Figure 2.—PBE DACS.

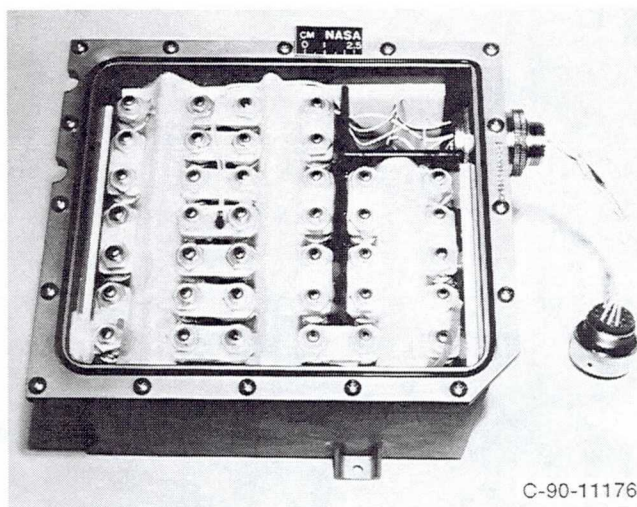


Figure 3.—Silver-zinc battery.

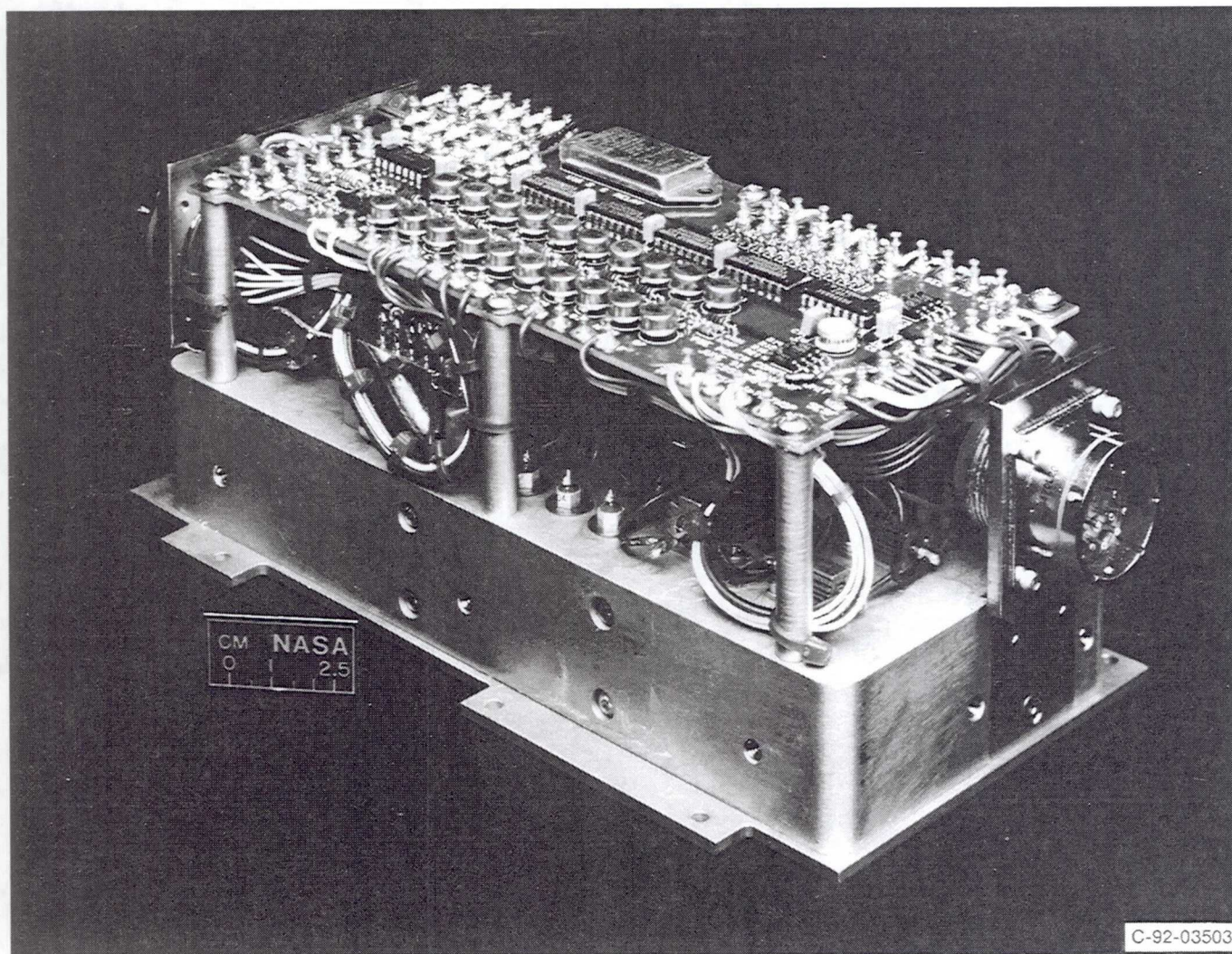


Figure 4.—Power Control Unit.



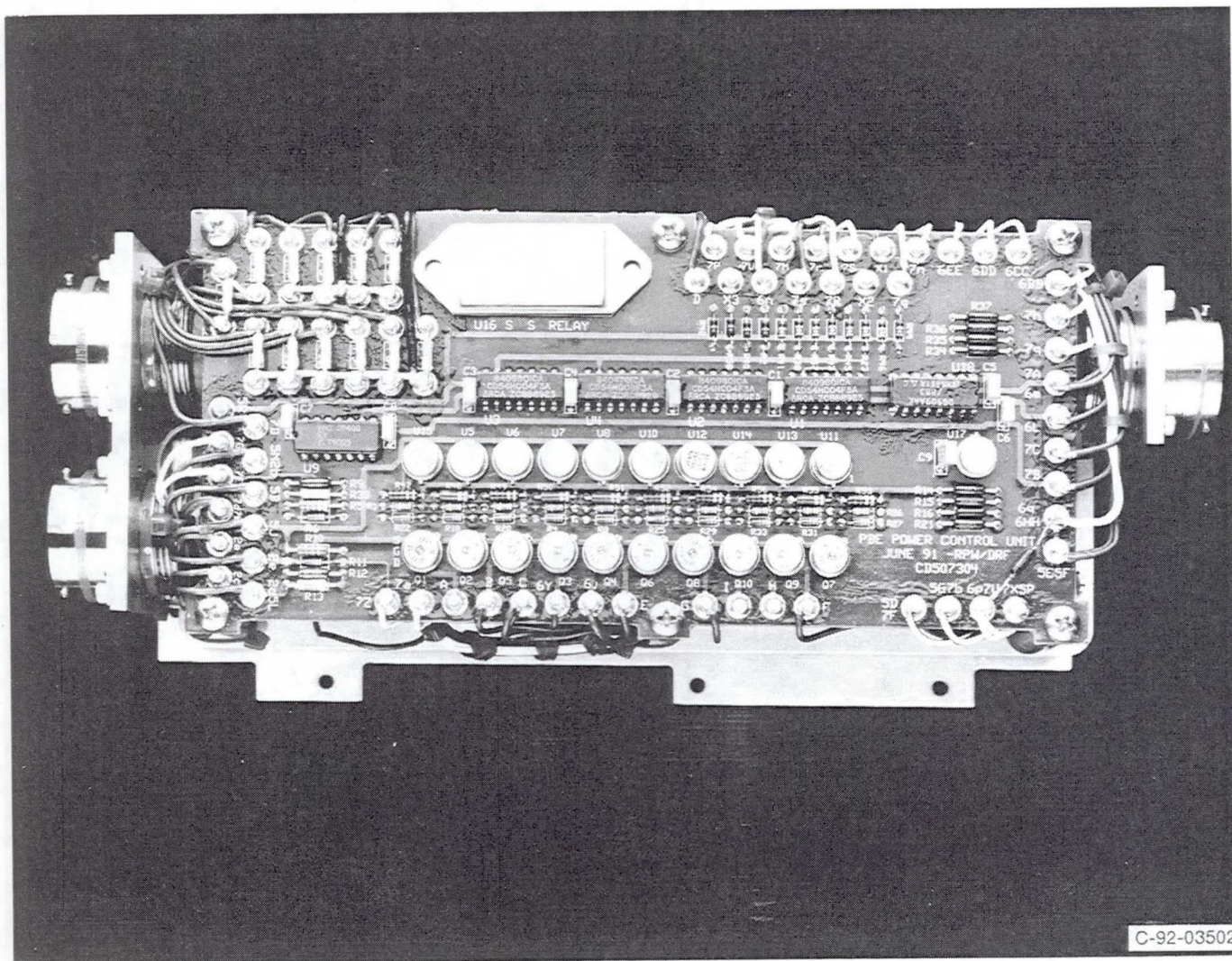


Figure 5.—Power Control Unit circuit board.



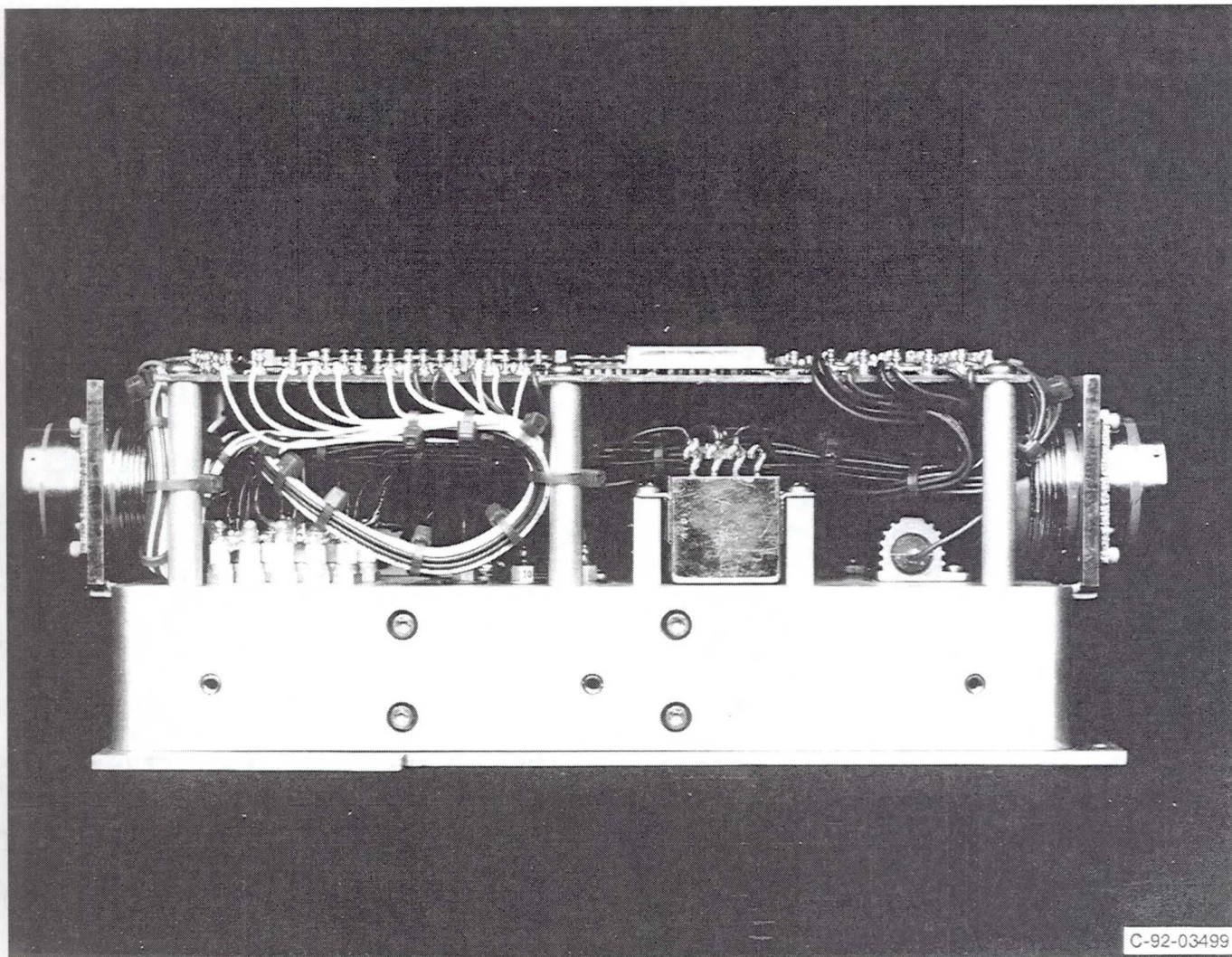


Figure 6.—Power Control Unit base.



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